10031842 .061002
10/031842
531 Rec'd PCT/PTC 22 JAN 2002
3/PRTS
[10191/2169]

DEVICE AND METHOD FOR ETCHING A SUBSTRATE BY USING AN INDUCTIVELY COUPLED PLASMA

The present invention relates to a device and a method which can be carried out with it, for etching a substrate, especially a silicon element, by using an inductively coupled plasma, according to the species defined in the independent claims.

Background Information

In order to implement an anisotropic high rate etching method, for instance, for silicon, using an inductive plasma source, it is necessary in one method, known, for example, from DE 42 41 045 C2, to carry out efficient sidewall passivation in as short a time as possible, during so-called passivating steps, and furthermore to achieve as high a concentration as possible of silicon-etching fluorine radicals during so-called etching steps. Here, in order to achieve an etching rate that is as high as possible, it is obvious to work with as high as possible an high-frequency power at the inductive plasma source, and thereby to couple in as high as possible plasma powers into the generated inductively coupled plasma.

However, there are limits to these high-frequency powers, which result on the one hand from load capacity of the electrical components of the plasma source, but, on the other hand, are also of a process technology nature. Thus, high-frequency powers of an inductive plasma source reinforce harmful electrical intervention by the source region in the inductively coupled plasma generated, which deteriorate the etching results on the substrate wafer.

Also, in etching processes according to the kind in DE 42 41 045 C2, stability problems appear in the coupling in of the

plasma in the changeover phases between etching and passivating steps. This is based on the fact that, in response to high power to be coupled in, in the kwatt range, power reflection and overvoltage appearing during the changeover phases can have a destructive effect on the electrical circuit of the plasma source (coil, connected capacitors, generator output stage).

On this point, German Application DE 199 00 179 describes an inductive plasma source, further refined compared to the one in DE 42 41 045 C2, which, with the aid of a loss-free symmetrical high-frequency supply of the coil of the inductive plasma source, is suitable for especially high plasma powers, and generates an inductive plasma which is particularly poor in electrical interference induced voltages. But for this source type too there exists a practicable power limit of about 3 kwatt to 5 kwatt, above which the required high-frequency components become extremely expensive, or, with respect to plasma stability, problems take the upper hand.

A possible approach towards attaining higher etching rates within a manageable power scope is to raise the efficiency of the plasma generation. In this connection, using magnetic fields to raise plasma efficiency is known in principle from the related art.

By applying a magnetic field to a plasma, as is well known, the electron paths in the plasma are bent, and because of that the residence time of the electrons in the plasma is increased, i.e. the time until they reach a wall which absorbs the electrons, so that each electron can interact more often with surrounding gas atoms until it leaves the effective plasma excitation region. Such impact interactions between electrons and gas molecules lead to the desired ionization or dissociation of the gas molecules along with the release of radicals needed for the etching process.

According to the related art, a so-called "multipole confinement" includes a metallic, nonferromagnetic wall having a plurality of permanent magnets of alternating polarity, which reflects electrons from the wall outfitted with these magnets, by the action of magnetic fields. Thereby, a higher electron density can be generated within this "multipole confinement". An analogous RIE (reactive ion etching) source is marketed, for example, by TEGAL Corporation, Petaluma CA 94955-6020, USA, as a so-called "HRe$^-$ Source".

Other known plasma source types further make use of a magnetic field having a field direction parallel to a substrate electrode. Thus, by using a kind of Helmholtz coil pair directly at the substrate electrode, a field distribution is generated that is as homogeneous as possible, which leads there to increased length of the electron paths, and thereby to the generation of greater plasma densities. For the further homogenization of the effects, this horizontally oriented magnetic field, as, for example, in the MRIE (magnetically enhanced reactive ion etching) equipment of Allied Materials, Inc., Santa Clara CA 95054-3299, USA, can further be rotated slowly in a planar manner.

In the case of so-called ECR (electron cyclotron resonance) sources, it is further already known that one should tune a longitudinal magnetic field in such a way that the circulation frequency of the electrons in this magnetic field, the so-called cyclotron frequency, is resonant with the frequency of the coupled in microwave radiation, at least in a certain volume range of the etching reactor. Thus, an especially efficient plasma excitation by microwave irradiation can take place at a sufficiently free path length of the electrons, which opens up to such ECR sources the low-pressure range of process pressures lower than 1 μbar as a field of application. In this connection, the low pressure is a necessary condition for a sufficiently great path length of the electrons and for efficient plasma excitation. At higher pressures, ECR sources

rapidly become inefficient, and go over to an unwanted thermal plasma generation. The advantage of the magnetic inclusion and the resonant excitation are thereby lost to a considerable extent.

It follows from the formula for the cyclotron frequency $\omega = eB/m$ that $B = m\omega/e$, i.e. at the usually irradiated microwave frequency of 2.45 GHz the magnetic field strength required for cyclotron resonance is 87.6 mTesla.

This application is not simply transferable to the case of high-frequency excitation in the MHz range, i.e. the case of typical frequencies for ICP (inductively coupled plasma) sources, since the free path lengths of the electrons, required for this, assume extremely low, impracticable pressures. After all, an inductive plasma source for high rate etching methods has to be configured for a relatively high pressure range of ca 30 to 100 μbar.

The usual high frequency of 13.56 MHz, used for inductive plasma excitation using ICP sources, would further, in the case of cyclotron resonance, imply a resonance field strength of only 0.5 mT. However, such a low field hardly has any remaining guidance function for the electrons. For a sufficient guidance function, i.e. suppression of wall losses of the electrons in an extended plasma volume, field strengths of 10 mTesla or rather several times 10 mTesla to 100 mTesla are required.

Magnetic coils in an ECR-type configuration are also usually placed above, or at the same height as the plasma source, so as to generate the greatest field strength directly at the location of plasma generation, and so as to have the greatest possible influence on the plasma generating mechanism there. In the direction of the substrate to be etched, then, the magnetic field strength decreases rapidly because of the divergence of the magnetic field, so that the guidance

function of the magnetic field is no longer sufficiently present in such an arrangement.

Varying plasma power coupled in an inductively coupled plasma having a high-frequency electromagnetic alternating field, adiabatically, between individual method steps, especially alternating etching and passivating steps, is further known from German Application DE 199 198 32. Such an adiabatic power transition, i.e. a gradual running-up or lowering of the coupled-in plasma power along with simultaneous continuous matching of the impedance of the ICP source to the respective plasma impedance as a function of the coupled-in plasma power, with the aid of an automatic matching network or an impedance transformer ("matchbox"), makes it possible to control the explained problems with regard to power reflection and voltage magnification in response to switching on and off plasma powers in the range of 1 kwatt to 5 kwatt. However, in this connection, a typical duration of transient effects lies in the range of 0.1 sec to 2 sec. Therefore, power changes cannot be made by this approach.

Summary of the Invention

Compared to the related art, the device according to the present invention has the advantage that it makes available a plasma etching equipment having inductive plasma generation or a plasma inductively coupled via an ICP source, in which an additional constant magnetic field, or one varying with time, considerably increases the efficiency of plasma generation. In this connection, the inductively coupled plasma generated, starting from the plasma source, is guided through the generated magnetic field in a kind of magnetic bottle to a substrate to be etched. For this purpose, a magnetic field coil or a sufficiently strong permanent magnet having longitudinal field direction is placed between the inductive plasma source (ICP source) and the substrate or a substrate electrode carrying the substrate, such as a silicon wafer.

Thus, when carrying out the method according to the present invention, this device effects a very efficient plasma generation in the area of inductive excitation, and a low-loss plasma transport right up to the substrate to be etched. At the same time, decoupling of plasma generation and the generation of the magnetic field is achieved. Because of the symmetry of the design of the device according to the present invention, in spite of the nonhomogeneous field distribution of the magnetic coil, good uniformity on the substrate surface continues to be maintained.

All in all, by using the generated longitudinal magnetic field, i.e. a magnetic field whose direction is at least approximately or predominantly parallel to the direction defined by the connecting line from the substrate to the inductively coupled plasma, the high-frequency power at the ICP source, required for high rate etching at the highest etching rates, is thus clearly reduced by efficient utilization of the coupled-in high-frequency power for generating the desired plasma species (electrons, ions, free radicals). Because of this, clearly higher etching rates are possible at equal plasma power.

Because the generation of the longitudinal magnetic field is placed between the ICP source and the substrate, both the substrate and the area of plasma generation in the reactor are in a region of relatively high magnetic field strengths, and, thus, of good guidance of the electrons and ultimately also the ions.

In addition, electrical interference effects coming from the source region can be effectively reduced by the improvement, achieved with the device according to the present invention, of the economics of the ICP source and the possibility, that goes with it, of reducing power without reducing the etching rate, or with etching rate increase at equal plasma power. On the whole, therefore, the etching result is achieved more

economically.

Furthermore, a power that is constant, pulsed or generally varying with time can be made available considerably more cost-effectively than a greater high-frequency power for coupling in the plasma. This power, by the way, demonstrates no harmful effect on the etching process or components of the plasma etching equipment.

Advantageous further refinements of the present invention result from the measures indicated in the dependent claims.

Thus, a particularly advantageous configuration of the device according to the present invention comes about if an aperture is additionally provided, positioned concentrically with the inner wall of the reactor, which is preferably arranged ca 5 cm above the substrate positioned on a substrate electrode. Such an aperture construction is known, for example, from German patent DE 197 34 278.

It is also advantageous if the plasma etching equipment according to the present invention is furnished with a balanced, symmetrically designed and symmetrically supplied configuration of the ICP source, as is proposed in German Application DE 199 00 179.

A magnetic field coil having an appertaining current supply unit is particuLarly suitable for generating the magnetic field, since with that, the generated magnetic field is timely, and, with regard to its strength, is variable and, in particular, pulsable.

It is also advantageous if an ICP coil generator is provided, which generates a variably adjustable, especially periodically varying or pulsed high-frequency power, which can be coupled into the inductively coupled plasma as plasma power.

It is also very advantageous if components are integrated into the ICP coil generator which carry out a variation of the frequency of the generated electromagnetic alternating field, for adapting the impedance as a function of the plasma power to be coupled in. An automatically acting feedback circuit having a frequency-selective component along the lines of a Meissner oscillator is particularly advantageously suitable for this.

Finally, it is very advantageous if the pulsing of the generated magnetic field is correlated in time or synchronized with the pulsing of the coupled-in plasma power and/or the pulsing of the high-frequency power coupled into the substrate via the substrate voltage generator.

Brief Description of the Drawings

Exemplary embodiments of the present invention are explained in detail in the following description, using the drawings. The Figures show:

Figure 1 a very schematic plasma etching equipment,

Figure 2 an electronic feedback circuit having a connected ICP source,

Figure 3 an example of a filter characteristic curve, and

Figure 4 an example of a correlation in time of high frequency power pulses and magnetic field pulses.

Exemplary Embodiments

A first exemplary embodiment of the present invention is explained in detail with reference to Figure 1. A plasma etching equipment 5 first of all has a reactor 15, in whose upper region an inductively coupled plasma 14 is generated in a manner known per se, via an ICP (inductively coupled plasma) source 13. The following are also provided here: a gas feed 19 for supplying a reactive gas such as SF_6, ClF_3, O_2, C_4F_8, C_3F_6,

SiF_4 or NF_3, a gas discharge 20 for removing reaction products, a substrate 10 such as a silicon body or a silicon wafer to be structured by the etching method according to the present invention, a substrate electrode 11 which is in contact with substrate 10, a substrate voltage generator 12 and a first impedance transformer 16. Substrate voltage generator 12 also couples in a high frequency alternating voltage or high frequency power into substrate electrode 11 and above that into substrate 10, causing acceleration of ions generated in inductively coupled plasma 14 onto substrate 10. The high-frequency power or alternating voltage input in this way is typically between 3 watts and 50 watts and 5 volts and 100 volts in continuous operation and in pulsed operation respectively, each averaged over time over the pulse sequence.

In addition, an ICP coil generator 17 is also provided, which is connected to a second impedance transformer 18, and above that with ICP source 13. Thus, ICP source 13 generates a high-frequency electromagnetic alternating field and also an inductively coupled plasma 14 composed of reactive particles and electrically charged particles (ions) formed by the action of the high-frequency electromagnetic alternating field on the reactive gas in reactor 15. ICP source 13 has a coil for this having at least one winding.

Second impedance transformer 18 is preferably designed in the manner described in German Patent 199 00 179, so that a balanced symmetrical designed configuration and supply of ICP source 13 over ICP coil generator 17 are obtained. This guarantees in particular that the high-frequency alternating voltages applied to the two ends of the coil of ICP source 13 are at least approximately in phase opposition to each other. Furthermore, the center tap of the coil of the ICP source is preferably grounded, as indicated in Figure 2.

The anisotropic high-rate etching process for silicon, having alternating etching and passivating steps, known from DE 42 41

045 C2, is further carried out, for example, using plasma etching equipment 5. With respect to further details, known per se to one skilled in the art, concerning plasma etching equipment 5, as described up to this point as being known from the related art, and the etching method carried out with it, especially with respect to the reactive gases, the process pressures and the substrate electrode voltages in each respective etching step or passivating step, as the case may be, we therefore refer to DE 42 41 045 C2.

Plasma etching equipment 5, by the way, is also suitable for supervisory control, as described in German Application DE 199 27 806.7.

During the etching of substrate 10, in particular during the passivating steps in reactor 15, passivating is carried out at a process pressure of 5 μbar to 20 μbar, and a plasma power, coupled into plasma 14 via ICP source 13, of 300 to 1000 Watt. C_4F_8 or C_3F_6, for example, are suitable as passivating gases. During the subsequent etching steps, etching is done at a process pressure of 30 μbar to 50 μbar and a high plasma power of 1000 to 5000 Watt. SF_6 or ClF_3, for example, are suitable as reactive gas.

A preferred embodiment of the plasma etching equipment further provides that, to improve the selectivity of an etching base polymer removal relative to the sidewall film removal, the ion acceleration voltage applied to the substrate by substrate voltage generator 12 be switched back by reduction of the coupled-in plasma power in the etching steps, each time after breakthrough of the initial etching base polymer, as has been proposed in German Application DE 199 19 832 and explained in detail.

This switching back here takes place in a manner known per se, either abruptly or continuously via a time-related ramp function. This achieves a further improvement of the silicon

etching rate, of the selectivity of the etchingprocess with respect to a masking material, the profile accuracy and, for example suppression of pockets in a dielectric etch-stop layer.

In addition, according to the present invention, a so-called "spacer" is further placed as spacer 22, made of a nonferromagnetic material such as aluminum, between inductively coupled plasma 14 or ICP source 13, i.e. The actual plasma excitation zone, and substrate 10. This spacer 22 is concentrically set into the wall of reactor 15 as spacer ring, and thus forms the reactor wall, from place to place. It has a typical height of ca 5 mm to 30 mm at a typical diameter of reactor 15 of 30 to 100 cm.

Spacer 22 further surrounds a magnetic field coil 21, which has, for instance, 100 to 300 turns and is wound with a lacquered copper wire of a sufficient gauge for the strength of current to be used. Additionally, copper pipes can be accommodated in magnetic field coil 21, having cooling water flowing through them so as to remove heat losses from magnetic field coil 21.

Alternatively, it is also possible to wind magnetic field coil 21 itself from a thin copper pipe lacquered with an electrically insulating material, and having the cooling water flowing through it directly.

An electric current such as 10 to 100 amp is conducted through magnetic field coil 21 via a current supply unit 23.

In the explained first exemplary embodiment this is, for example, a d.c. current which generates a static magnetic field on the inside of reactor 15, which, in the case of a magnetic field coil 21 having 100 turns and a length of 11 cm as well as a diameter of 40 cm generates a magnetic field strength in the center of magnetic field coil 21 of about 0.3

mTesla/A of current flow.

For a significant increase of plasma generating efficiency and sufficient magnetic guidance of inductively coupled plasma 14, 10 mT to 100 mT, for instance 30 mT, are required, as has already been explained. That means, that current supply unit 23 makes available current strengths of about 30 to 100 amp during etching of a substrate 10, using plasma etching equipment 5.

Instead of magnetic field coil 21, by the way, a permanent magnet can be used. Such a permanent magnet advantageously requires no energy, but has the disadvantage that setting the magnetic field strength, which is of advantage for setting an optimum etching process, is not possible. Besides, the field strength of a permanent magnet is temperature dependent, so that magnetic field coil 21 is preferred.

It is important in each case that the direction of the magnetic field generated by magnetic field coil 21 or by the permanent magnet is at least approximately or predominantly parallel to the direction defined by the connecting line of substrate 10 and inductively coupled plasma 14 or the plasma generating zone (longitudinal magnetic field orientation).

An advantageous refinement of the explained exemplary embodiment further provides for installing an aperture known from DE 197 34 278, for improvement of the uniformity of the etching process. For reasons of clarity, this aperture is omitted in Figure 1. It is mounted on the inside of reactor 15, concentrically with the reactor wall, between ICP source 13 or the plasma excitation zone and substrate 10. It is preferably fastened on spacer 22, ca 5 cm above substrate electrode 11 or substrate 10.

Also, in case of the use of a magnetic field coil 21, a suitable monitoring device, known per se, has to be integrated

into current supply unit 23, the monitoring device being integrated into the process sequence control, and carrying out monitoring of the coil temperature and emergency switching-off, for example, when there is a shortage of cooling water.

In the first exemplary embodiment, during etching, ICP coil generator 17 couples continuously during the etching steps or the passivating steps an at least to a great extent constant plasma power of a minimum of 300 Watt to a maximum of 5000 Watt into inductively coupled plasma 14.

In particular, during the passivating steps, a plasma power of 500 Watt is coupled into inductively coupled plasma 14, and during the etching steps a plasma power of 2000 Watt is coupled into inductively coupled plasma 14; ICP coil generator and second impedance transformer 18, in the manner known from DE 199 198 32 and explained above, in response to a transition from a passivating to an etching step, carrying out an adiabatic up-regulating of the coupled-in plasma power over a time-related ramp function and, at the same time, via second impedance transformer 18, an automatic, stepwise or continuous impedance adaptation.

A second exemplary embodiment of the present invention provides that, as a modification of the first exemplary embodiment, instead of adiabatic control of the high-frequency power coupled into the inductively coupled plasma 14 by IPC source 13, and instead of a matching of the coupled-in high frequency power given at any point in time, via the automatic matching network ("matchbox") as the second impedance transformer 18, to the plasma impedance changing with increasing plasma power, alternatively the previously constant frequency of the high frequency electromagnetic alternating field, which ICP coil generator 17 produces, should be varied for impedance matching.

The matchbox, preferably symmetrically designed and supplying ICP source 13 symmetrically in second impedance transformer 18 is, in this connection, preferably set in such a way that it ensures an optimum impedance matching in the steady-state power case. This steady-state power case is characterized in that, in this connection, the plasma power inductively coupled into plasma 14 has reached a high maximum or final value such as 3000 watt to 5000 watt, a steady-state frequency or a resonant frequency 1'' of, for example, 13.56 MHz of the frequency produced by ICP coil generator 17 of the high frequency electromagnetic alternating field having simultaneously been reached.

The steady-state frequency 1'' of customary ICP coil generators 17 is generally 13.56 MHz, besides this standard, generators having other frequencies or frequency ranges also being commercially obtainable. However, in such ICP coil generators 17, in deviation from the realization according to the present invention, the steady-state frequency 1'' is set to a fixed value which is, for example, derived with great accuracy from the natural frequency of a quartz-crystal oscillator. Thus, during a power change, for example, during the run-up of the plasma power to be coupled into plasma 14 from, for instance 500 watt to 3000 watt at a steady frequency of the high-frequency of high-frequency alternating field generated by ICP coil generator 17, with a predefined setting of impedance transformer 17, no matching, or only a bad one, to the plasma impedance changing as a function of the plasma power is possible, so that high reflected powers appear during the transients. However, if the frequency of ICP coil generator 17 is enabled in such phases, then by a change in the frequency of the high-frequency electromagnetic alternating field, a substantially optimum impedance adaptation, even under quickly changing plasma conditions, can be maintained.

The essential advantage of the production of the correct

impedance matching via a variable frequency of the high-frequency power of coil generator 17 is that this frequency change can be carried out very fast because it is limited only by the control rate of the corresponding electronic circuit. That makes possible reaction times in the microsecond range, without any problem.

In contrast to that, manual or automatic setting of an matching network requires the change of mechanical quantities in second impedance transformer 18, for example the resetting of variable capacitors by motors, which takes place correspondingly slowly. Typical time constants here lie in the range of tenths of seconds.

In a preferred design of the second exemplary embodiment, a control circuit integrated in second impedance transformer 18, for example, in a manner known per se, detects the instantaneous control error, i.e. the faulty adaptation of the impedance of the output of ICP coil generator 17 and the impedance of ICP source 13, with respect to amplitude and phase. This takes place preferably by a measurement of the signal reflected at ICP source 13 or second impedance transformer 18, using reflectometers sufficiently known from high-frequency technology, amplitude and phase errors being detected.

From this information, a corresponding frequency change of the electromagnetic alternating field at ICP coil generator 17, required in each case, is ascertained, preferably continuously within a predefined frequency range, so that the control errors with respect to amplitude and phase can be minimized. This basically only corrects an amplitude error, since, as is well known, to a great extent only the real plasma resistance changes as a function of the coupled in plasma power, and the phase relationship of the impedances is set correctly, at least roughly, just by the explained presetting of second impedance transformer 18.

When the output power of ICP coil generator 17, and with that also the plasma impedance finally become steady-state after completion of the run-up of the plasma power, the control circuit takes the frequency of ICP coil generator 17, or of the electromagnetic alternating field generated, back to the actually desired fixed value such as 13.56 MHz, and fixes it there. In this connection, for the frequency in the case of the steady-state power, second impedance transformer 18 is set correctly via the presetting ascertained before, which, of course, is a function of the maximum plasma power to be reached, and this can be done either manually or automatically, using low-speed control characteristics.

To sum up, if the frequency of ICP coil generator 17 is thus fixed, in the steady-state case of the power to be coupled in, at, for example, 13.56 MHz, whereas, during the course of the unstable run-up phases of the generator output power, the frequency is temporarily released within a certain bandwidth, and is controlled by an electronic control system for impedance matching. Thus it is possible to carry out even very fast power changes of the generator output power in the range of microseconds in a stable manner, at simultaneous high power changes, which is not possible using known matching networks or impedance transformers.

This is explained, for example, with the aid of Figure 3, in which a filter characteristic line 1' is represented, which shows a preset frequency range within which the frequency of ICP coil generator 17 may be varied, each frequency being assigned a certain high-frequency power or plasma power to be coupled in, or a coupling loss A of the power of ICP coil generator 17. The frequency to be reached in the case of steady-state power, in this connection, is the steady-state frequency 1'', which may be 13.56 MHz, for example, and at which the predefined maximum power is supplied as the plasma power to inductively coupled plasma 14.

An especially preferable third exemplary embodiment of the present invention, in continuation of the second exemplary embodiment explained above, further provides leaving the frequency variation of ICP coil generator 17 to an automatically acting feedback circuit, so that one can do without measuring the faulty adaptation in each case or measuring the reflected signals, for example, by reflectometer. This is explained in more detail with the aid of Figure 2.

In this connection, ICP source 13, i.e. its coil, to be exact, in a manner known per se from DE 199 00 179, is first energized by a preferably balanced symmetrical matching network 2 from an unbalanced unsymmetrical output of ICP coil generator 17. Adaptation network 2 is a part of second impedance transformer 18.

The ICP coil generator 17 is further, in this case, made like a widespread specific embodiment, including a high-frequency power element 3 and a quartz oscillator 4 for producing a high-frequency fundamental wave having a fixed frequency such as 13.56 MHz.

In the related art, the high frequency fundamental wave of quartz oscillator 4 is normally supplied to the amplifying input of power element 3. According to the present invention, however, this supply is modified in such a way that quartz oscillator 4 is made accessible separately from the amplifier input of power element 3, and its input is made accessible externally, for instance via a corresponding input socket. Since the quartz oscillator in this specific embodiment no longer has a function, it can actually be suitably deactivated.

Power element 3 further has generator control inputs 9 in a known way, which are used for external control of ICP coil generator 17. Using them makes possible, for example,

switching on and off ICP coil generator 17 or the stipulation of a high frequency power to be generated. In addition, generator status outputs 9' are possible, for the feedback of generator data such as, for instance, generator status current output power, reflected power, overload, etc, to an external control unit (machine control) not shown, or to current supply unit 23 of plasma etching equipment 5.

The amplifier input of power element 3 is now suitably connected to ICP source 13, in the sense of a feedback circuit via a frequency-selective component 1.

In this connection, additionally, capacitors, inductance coils and resistors or combinations of these can be interconnected and provided in a known manner as voltage dividers, in order to weaken the high voltages that appear at the coil of ICP source 13 to a suitable measure for frequency-selective component 1 or the amplifier input of power element 3. Such voltage dividers belong to the related art, and are indicated in Figure 2 only by a decoupling capacitor 24 between the coil of ICP source 13 and frequency-selective component 1. Alternatively, one can also move signal tap 25 to the vicinity of the drawn-in grounded center point or center tap 26 of the coil of ICP source 13, where correspondingly lower voltage levels are present. Depending on the distance of the signal tap, which, for example, can be designed as an adjustable clip contact, from grounded center tap 26 of the coil of ICP source 13, a larger or smaller tapped voltage can be set, and thus favorable level ratios can be achieved.

Frequency-selective component 1 is represented in the example as a tunable arrangement of coils and capacitors, so-called LC resonant circuits, which together form a band-pass filter. This band-pass filter has as conducting state region a certain predefined bandwidth such as 0.1 MHz to 4 MHz, and a filter characteristic line 1', as shown as an example in Figure 3.

In particular, the band-pass filter has a resonance or steady-state frequency 1'' having maximum signal transmission. This steady-state frequency 1'' is preferably 13.56 MHz and can be fixed exactly, for example, by a quartz-crystal oscillator 6 or a piezoceramic filter element as additional components of the band-pass filter.

Alternatively, it is also possible, instead of LC resonant circuits, to combine so-called piezoceramic filter elements, or other known frequency-selective components known per se, into a band-pass filter having the desired filter characteristic line, bandwidth and steady-state frequency 1''.

The set-up described above controlled power element 3, matching network 2, ICP source 13 and band-pass filter represents in total a feedback circuit of the same kind as a Meissner oscillator.

During operation, this first begins to oscillate in the neighborhood of steady-state frequency 1'', in order to build up to a predefined output power of power element 3. The phase relationship, required for the build-up, between generator output and signal tap 25 is set correctly for this purpose once, in advance, for example, via a delay line 7 of specific length, and with that, via the phase shift defined by the signal propagation time or a phase shifter instead of delay line 7. This ensures that the coil of ICP source 13 has damping reduced with a correct phase.

Via delay line 7 it is further especially ensured that, at the location of ICP source 13, the driving electrical voltage and the current in the coil of ICP source 13 have a resonance phase of approximately 90^0 to each other.

In practice, by the way, the resonance condition of the feedback circuit with regard to frequency-selective component 1 is not severe, so that, in general, a small frequency shift

in the neighborhood of resonance or steady-state frequency 1'' is sufficient for almost automatically correcting the resonance condition with respect to the phase. Therefore it is sufficient to correct the resonance condition only approximately by the outer circuit elements, so that the resonant circuit builds up somewhere close to its steady-state frequency 1''.

However, if all phase shifts from signal tap 25 of the coil of ICP source 13 via the band-pass filter into the input of power element 3, and through the power element back to second impedance transformer 18 into the coil of ICP source 13 should sum up so unfavorably that actually dumping instead of damping reduction of the resonant circuit takes place, the system cannot begin to oscillate. The feedback then becomes an unwanted negative feedback instead of the desired positive feedback. The setting of this approximately correct phase is accomplished by delay line 7, whose length should therefore be set at one time in such a way that the feedback acts constructively, i.e. to reduce damping.

All in all, in the case of faulty adaptation to the plasma impedance, for example, during rapid power changes, the explained feedback circuit can thus give way in its frequency within the band pass of the band-pass filter, and always maintain a largely optimum impedance matching, even during rapid impedance changes of inductively coupled plasma 14.

Then, as soon as inductively coupled plasma 14 stabilizes with regard to the plasma impedance or the coupled-in plasma power, the frequency of ICP coil generator 17 will return again to near or exactly the value of the maximum pass frequency, which is given by the resonant frequency or steady-state frequency 1''. This matching of the impedance by frequency variation takes place automatically and very rapidly within a few periods of oscillation of the high frequency voltage, i.e. in the microsecond range.

The connection between the output of power element 3 and the input of second impedance transformer 18 is made, by the way, by line 8, which is designed as a coaxial cable, and is capable of carrying a power of a few kwatt.

With this automatically building up arrangement, or even with the arrangement described before, having active frequency control for matching to rapidly changing plasma impedances, it is advantageously possible also to perform a pulsed operation of the inductive plasma source.

Now, in the case of the refinement of the ICP coil generator described in the fourth exemplary embodiment it is further possible also to perform a pulsed operation of ICP source 13, and thereby, for example, also to couple in pulsing plasma power during the etching or passivating steps of the etching method.

To do this, the output power of ICP coil generator 17, for instance, is periodically switched on and off using a repetition frequency of typically 10 Hz to 1 MHz, preferably 10 kHz to 100 kHZ, i.e. it is pulsed, or the envelope curve of the output voltage of ICP coil generator 17 has its amplitude modulated by a suitable modulating voltage. Such devices for amplitude modulation are sufficiently well known from high frequency technology.

For example, generator control input 9 can be used to select the setpoint value of the high frequency power of ICP coil generator 17 for the purpose of supplying the signal modulating the high frequency power of ICP coil generator 17.

Since, in response to a pulsed operation of ICP source 13, very rapid impedance changes appear in plasma 14, according to the related art up to now, it is impossible, especially with power in the kwatt range, to avoid the occurrence of high reflected power during switching on and off coupled-in high

frequency power pulses, or at least to make these harmless.

In contrast, by using the device explained in this exemplary embodiment, the impedance matching of inductively coupled plasma 14, or ICP source 13, and ICP coil generator 17 is ensured at all times, in this case as well.

Compared to a continuous operation, a pulsed operation of ICP source 13 has the further advantage that, during the high frequency power pulses or during the plasma power pulses a substantially higher plasma density can be achieved than in continuous operation. This is based on the fact that generation of an inductive plasma is a high-grade nonlinear process, so that the average plasma density in this pulsed operational mode is higher than in the case of an average plasma power corresponding to the time average.

Therefore, in pulse operation one effectively obtains more reactive species and ions with respect to the time average than in continuous operation. This is true especially when so-called "giant impulses" are used, i.e. relatively brief and extremely high-powered high frequency power impulses such as 20 kwatt peak power, as is now possible with the device according to the present invention, the average plasma power at time average being then, for example, only 500 watt.

In this connection, unavoidable heat losses in ICP coil generator 17 and other equipment components of plasma etching equipment 5 are then correlated with the relatively low time-averaged value of the plasma power, whereas desired plasma effects, particularly the achievable etching rates, advantageously correlate with the occurring peak powers. As a result, the efficiency of generation of reactive species and ions is clearly improved.

In this connection, of course, ICP coil generator 17 and the remaining components of plasma etching equipment 5 involved

have to be designed in such a way that they can process even the occurring peak loads (peak currents and peak voltages) without damage. On account of the high voltage peaks at the inductive coil, the balanced supply of the ICP coil has an especially advantageous effect on obtaining favorable plasma properties.

A further considerable advantage of pulsed operation of ICP source 13 is that interfering electrical charges on substrate 10 to be etched can be discharged during the pauses between the high frequency power pulses, and profile control during etching can thereby be improved in toto.

Typical pulse/pause ratios, by the way, lie between 1:1 and 1:100, the average plasma power typically being 100 watt to 1000 watt. The amplitude of the individual high frequency power pulses effectively lies between 500 watt and 20,000 watt, preferably at ca 10,000 watt.

In continuation of the fourth exemplary embodiment, a fifth exemplary embodiment additionally provides that first, as already explained above, a pulsed inductively coupled plasma 14 is generated in an ICP source 13, using magnetic field support. In this connection, the magnetic field generated by magnetic field coil 21, which was always held constant at least to a great extent with respect to time, in the preceding exemplary embodiments, is now also pulsed.

Especially preferably, this pulsing of the magnetic field, which is brought about in a simple manner by correspoding current pulses generated by current supply unit 23, takes place in such a way that the magnetic field is only generated if simultaneously also a high frequency oscillation packet or a high frequency power pulse for generating or coupling in plasma power into inductively coupled plasma 14 is present at ICP source 13. As long as no plasma power is coupled in or no plasma is excited, as a rule no magnetic field support is

required either.

A possible and preferable synchronization in time of high frequency power pulses for coupling in plasma power in plasma 14 and current pulses through magnetic field coil 21 is explained, in this connection, with the aid of Figure 4.

Here, the coil current is switched on by magnetic field coil 21 in each case shortly before the application of a high frequency oscillation packet, i.e. a high frequency power pulse, and is switched off again after the end of this pulse.

Synchronization of current and high frequency power pulses can be ensured in a simple way, in this connection, by an impulse generator known per se, integrated into current supply unit 23, for example, which is furnished with additional time elements, in order to connect to the supply the high frequency power pulse with a certain delay of, for example, 10% of the set high frequency impulse duration after switching on the current of magnetic field coil 21, or to switch this current off again with a certain delay of, for example, 10% of the set high frequency impulse duration after the end of the high frequency power impulse. Such synchronization circuits and corresponding time elements for generating the needed time delays are in the related art and are generally known. For this, current supply unit 23 is further in connection with ICP coil generator 17.

Synchronization of the pulsing of magnetic field and coupled-in plasma power has the great advantage that thereby the ohmic heat losses arising in magnetic field coil 21 can be clearly reduced. Thereby the problems of cooling and temperature control are deactivated.

If, for example, the coupled-in plasma power is operated with a pulse/pause ratio of 1:20, the current can also be pulsed by the magnetic field coil at, for example, a pulse/pause ratio

of 1:18. In this connection, the duration of a current impulse by magnetic field coil 21 is always a little longer than the duration of a high frequency power pulse.

By this procedure, heat removal of magnetic field coil 21 is reduced to 1/18 of the original value. At the same time, use of electrical energy is reduced correspondingly.

Typical rates of repetition or pulse rates are oriented to the inductance of magnetic field coil 21, which limits the speed of change of the coil current. A rate of repetition of a few 10 Hz to 10 kHz is realistic for most magnetic field coils 21, depending on their geometry. Typical pulse/pause ratios for the high frequency power pulses lie between 1:1 and 1:100.

In this connection it is further very advantageous to apply the aperture, known from DE 197 34 278 and already explained, below magnetic field coil 21, a few cm above substrate 10 or substrate electrode 11, which carries substrate 10.

The use of this aperture improves, on the one hand, uniformity of the etching over the substrate surface, especially clearly with a symmetrically supplied ICP source 13. At the same time, the time-variable magnetic field - the transients - is also reduced at the location of substrate 10. In this connection, eddy currents in the aperture ring of the aperture lead to a dumping of the time-variable magnetic field components directly before substrate 10, so that induction processes on substrate 10 itself are weakened.

Such changing magnetic fields, so-called transients, could induce voltages in antenna structures on the substrate, which on their part could again lead to damage to the substrate, if the latter, for example, has integrated circuits or especially field effect transistors.

As for the rest, it should be emphasized that it is further

advantageous also to pulse the high frequency power, present at substrate 10 via substrate electrode 11, which is generated by substrate voltage generator 12 for the acceleration of the ions. This pulsing is then preferably also done correlated in time, or synchronized, with the pulsing of the magnetic field and/or the pulsing of the coupled-in plasma power.

List of Reference Numerals

1	frequency-selective component
1'	filter characteristic line
1''	steady-state frequency
2	matching network
3	power element
4	quartz oscillator
5	plasma etching equipment
6	quartz-crystal oscillator
7	delay line
8	line
9	generator control input
9'	generator status output
10	substrate
11	substrate electrode
12	substrate voltage generator
13	ICP source
14	inductively coupled plasma
15	reactor
16	first impedance transformer
17	ICP coil generator
18	second impedance transformer
19	gas supply
20	gas exhaust
21	magnetic field coil
22	spacer
23	current supply unit
24	decoupling capacitor
25	signal tap
26	center tap